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DEVELOPMENT OF RADIATION PYROMETRY TECHNIQUES FOR MEASUREMENT OF TEMPERATURE DURING THE ROLLING OF URANIUM

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May 1, 1953

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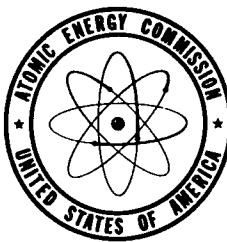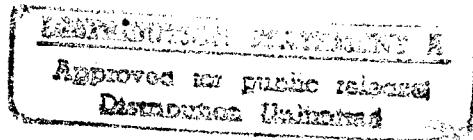
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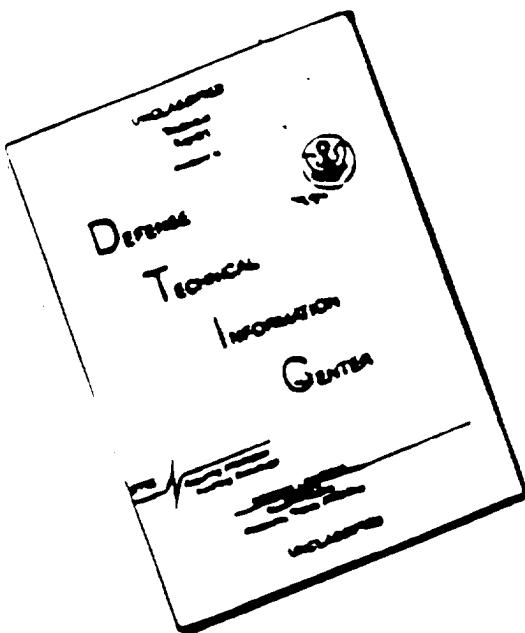
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Work performed under Contract No. AT(30-1)-1316

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I. ABSTRACT

This report covers work performed on Contract AT(30-1)-1316 between the Brown Instruments Division of the Minneapolis-Honeywell Regulator Company and the New York Operations Office of the Atomic Energy Commission.

The emittance of salt-coated uranium (a eutectic mixture of lithium and potassium carbonates) was found to be about 0.86 between the temperatures of $900^{\circ}F$ and $1200^{\circ}F$. The emittance of uranium oxide (U_3O_8) was found to be about 0.82; the emittance of the salt mixture was 0.9; and the emissivity of uranium metal between $200^{\circ}F$ and $600^{\circ}F$ was 0.15.

A holder and housing for the Brown Miniature Radiamatic Radiation Pyrometer was developed which was flexible and could be used to advantage measuring the temperature of uranium ingots and bars during the rolling operation. A number of these units were fabricated for the Feed Materials Center at Fernald, Ohio.

A calibration panel was designed and built which permitted easy calibration of the Radiamatic assemblies. This panel contained a blackbody furnace as a radiation reference source.

A considerable amount of time was spent during the spring of 1952 working at the experimental rollings held at several steel mills. This work was in addition to the laboratory work and was more of an

application and installation nature.

II. INTRODUCTION

This is the final report of the work on the measurement of temperature during the rolling of uranium performed under Contract AT(30-1)-1316 between the Brown Instruments Division of the Minneapolis-Honeywell Regulator Company and the New York Operations Office of the Atomic Energy Commission.

The Brown Instruments Division first entered the temperature measurement program to provide limited assistance to the Production Division of the New York Operations Office of the Atomic Energy Commission and the Catalytic Construction Company which were engaged in the development of rolling practices and the construction of rolling facilities at Fernald, Ohio. It soon became apparent that the solution of the many problems associated with temperature measurement during rolling would entail a considerably expanded project of instrument development. This contract was therefore drawn up with the New York Operations Office under the auspices of the Research Division. During the entire period of this contract, a program of mutual participation was maintained with the Research Division, the Production Division, the National Lead Company of Ohio, and the Catalytic Construction Company.

The contract was divided into three parts. Part One was concerned with investigation of the emittance of uranium rods and billets when bare and when coated with a molten salt. Also included in Part One

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was investigation of the various characteristics of the miniature

Radiamatic, which were of importance to this application. Part

Two was concerned with application of the information obtained

in Part One to the experimental rollings held during the spring of

1952. Part Three covered the development of holders and equipment

which would allow the miniature Radiamatics to be easily used at

Fernald. A method of calibrating the Radiamatics in the field was

also required. It was deemed necessary that all Radiamatic

receivers used at Fernald be interchangeable, which required the

addition of a calibrating adjustment in the Radiamatic housing.

Part Two required considerable field assistance at the experimental

rollings.

III. THE NUCLEAR ENGINEERING LABORATORY

Laboratory Facilities

The project was undertaken at the Nuclear Engineering Laboratory of the Brown Instruments Division. The laboratory was located at the Olney Plant of Brown but was moved to the Louden Street Plant during the period of the contract.

The laboratory was set up to handle investigations of a classified nature and little modification was necessary to include this work. Aside from the standard office and laboratory equipment, the following special equipment was obtained to permit handling of the radioactive material used.

1. Machine lathe

2. Drill press

3. Grinder

4. Beam scale

5. Vacuum cleaner

6. Fume hood

7. Salt bath

The salt bath consisted of a one-cubic-foot ceramic kiln in which a cast-iron crucible was fitted. The temperature of the bath was controlled with a circular chart recorder-controller and was

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capable of maintaining the salt at $1300^{\circ}F$ for extended periods of time. Some difficulty was experienced with splashed salt corroding the heating coils, but in general the salt bath worked very successfully and proved to be a quick and cheap method of obtaining a salt bath.

Project Personnel

The abbreviated organization chart given below indicates the position of the Nuclear Engineering Laboratory in the Brown Instruments Division.

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+---------------------------------------+
|      Research and Development         |
|        W. P. Wills, Manager           |
+---------------------------------------+
                  |
+---------------------------------------+
|     Physical Measurements Section     |
|    R. O. Anderson, Section Leader     |
+---------------------------------------+
                  |
+---------------------------------------+
|     Nuclear Engineering Laboratory    |
|        J. V. Werme, Supervisor        |
+---------------------------------------+
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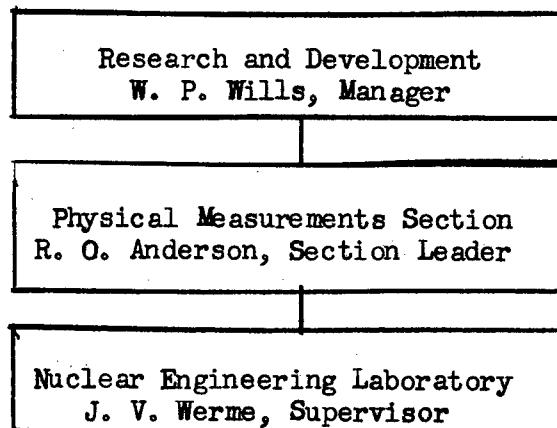
The experimental investigations were conducted by C. W. Ricker and H. F. Schaf, Jr. The final models of the special Radiamatic, the universal joint and the universal holder were designed by C. F. Robinson while temporary assistance was given by P. J. Donald and J. Vollmer. Miss Virginia Ratcliffe handled the typing, filing, and

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assisted in the preparation of this report.

IV. THE RADIAMATIC RADIATION DETECTOR

The Miniature Radiamatic Detector and Accessories

The Brown Miniature Radiamatic, Model 939A4, was considered the
best of the several total radiation pyrometers available for this
project. About a dozen of these instruments were already in use
at the experimental rollings when the project was started, but
various modifications were found to be necessary as will be described
herein.

The Miniature Radiamatic, shown in Fig. 1, consists of an
aluminum case which houses a calcium fluoride lens and a thermopile
assembly. The lens transmits visible and infra-red radiation in the
0.03 to 10 micron range. The thermopile assembly is a two-piece
aluminum cylinder which contains a thermopile, shown in Fig. 2, and
an ambient temperature compensation coil. The thermopile consists
of ten Chromel-Constantan thermocouples connected in series and coated
with carbon black to increase the absorption. Ambient temperature
compensation up to 250°F is provided by means of a nickel-compensating
coil in the thermopile circuit.[1]

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[1]
Harrison, T. R. and Wannamaker, W. H., RSI, Vol. 12, No. 1,
p. 20, 1941.

The instrument is usually calibrated in the field. This is accomplished by means of an adjustment in the span of a strip chart recorder. If the recorder and Radiamatic are calibrated at one temperature and the object which is being looked at is a black or greybody radiator,[1] the instrument will be in calibration at all temperatures. A chart and scale covering the range between 300°F and 1300°F was picked for this application.

Problems Encountered in Radiation Temperature Measurements

The determination of the temperature of metal bars as they leave the rolls in a rolling mill presents several problems. There is the problem of determining the temperature of the bar at one standard temperature in order to calibrate the system. This will be discussed in a following section. Next, a mounting system and a cone-of-sight must be established which keeps the bar properly in sight at all times, because the bars under consideration are relatively small (1 to 3 inches in diameter) and are subject to considerable lateral and vertical motion as they leave the rolls. The third problem which was met here was the question of establishing calibrating means

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[1]A graybody is defined for this report as a body whose emittance is constant over an entire range of temperature. Frequently, a graybody is defined as a body whose spectral emittance is constant throughout the emitted spectrum.

within the Radiamatic in order to make all the units in a given area interchangeable.

The following method of mounting the Radiamatic and limiting the field of view was employed before the start of this project. An iron tube about 5 inches long and $1\frac{1}{2}$ inches in diameter was mounted on the frame of the rolls at each station with the Radiamatic held loosely in the tube. The major disadvantages of this arrangement were: (1) loose mounting allowed the Radiamatic to be moved by the machine vibration, (2) the Radiamatic was relatively unprotected in case of a "cobble" where the rolled billet twists out of control as it jams in the rolls, (3) the aperture of the sighting tube did not sufficiently limit the cone of sight of receiver.

The later version of the sighting tube consisted of a copper tube about 1-1/4 inches in diameter and 5 inches long. One end of the tube was fitted by force to the neck of the Radiamatic shell. The other end of the tube was formed into a rectangular slot about 1/4 inch wide and $1\frac{1}{2}$ inches long. In practice, the Radiamatic and sighting tube were strapped to an adjustable iron bracket which was attached to the roll stand. When the Radiamatic was placed with the long side of the slot parallel to the line of travel of the bar being rolled, the area of sight was sufficiently restricted to permit rigid mounting. The disadvantages of this system were many. The

force fit of the sighting tube to the Radiamatic was difficult to maintain; the long axis of the slot had to remain parallel to the direction of rod movement, and although a cobble was no longer a danger, the initial adjustment was difficult and time consuming.

The next modification of the sighting tube was similar to the last, but the slot was replaced by a spun conical section. This section made it possible to dispense with the necessity of maintaining the slot and the rod parallel, but the rest of the troubles were still there.

Design of the Radiamatic Assembly and Mounting

The final design of the sighting tube, Radiamatic housing, and mounting equipment is shown in Fig. 3. The sighting tube, A, is a copper tube with a spun, truncated cone on one end and a flange on the other. The inside is painted dull black to minimize internal reflections. The sighting tube is bolted to the miniature Radiamatic, B. The Radiamatic has a back cap, C, which contains a 500-ohm, wire-wound potentiometer for calibration and also protects the back of the detector from dirt and water. There is a shielded, two-conductor cable emerging from the cap for connection to a recorder or terminal block. A universal mounting, D, attached to the Radiamatic and a universal joint, E, are also provided. The universal mounting and flange have half-inch pipe threads in order to make it

easy to join them with standard pipe. A completely assembled unit
is shown at the top of the photograph. Great flexibility in mount-
ing may be obtained with this system and it is easy to properly
position the Radiamatic over the work.

Detail drawings of all of the parts are on file at the New
York Operations Office of the Atomic Energy Commission.

The Brown Miniature Radiamatic, Model 939A4, total radiation
pyrometer, has as a detector a thermopile whose physical features
were described earlier.

The design of the thermopile is such that most of the heat
which is lost from the hot junctions is lost by conduction, rather
than by radiation. A thermopile which loses a good part of its heat
by conduction is less sensitive than one which loses its heat by
radiation, but is much less subject to errors due to fluctuations
in the ambient temperature of the detector housing. In a thermo-
couple designed to lose heat by radiation, the temperature of the
hot junction is dependent mainly on the work temperature and almost
not at all upon the shell temperature when the work is considerably
warmer than the shell. Consequently, fluctuations in the ambient
temperature of the shell can lead to large errors in temperature
reading due to the change in the temperature difference between the
thermopile and the shell. In a thermopile designed to lose heat

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by means of conduction, the temperature of the hot junction depends also upon the shell temperature of the pyrometer. As a result, the temperature of the hot junction tends to change with shell or cold junction temperature. These changes are such that, for a given work temperature, the difference between hot and cold junction temperature tends to remain constant as the cold junction temperature varies. The ratio of cold to hot junction temperature is not exactly constant over a range from $50^{\circ}F$ to $250^{\circ}F$ but is small enough to be correctible. This is accomplished by means of a nickel coil which shunts the thermo-pile and which is so located as to be at the temperature of the cold junction at all times. The temperature-resistivity characteristic of the coil is such that the shunt resistance of the coil varies in a manner which alters the net output of the Radiamatic so as to maintain a nearly constant output for a given work temperature when ambient temperatures vary between $50^{\circ}F$ and $250^{\circ}F$. For a detailed explanation of the choice of the thermopile design employed in the Radiamatic together with an analysis of the theory upon which the design is based along with experimental data to show the results of the theory, consult the paper of T. R. Harrison and W. H. Wannamaker cited above.

Temperature Compensation Experiment

Experiments to determine long-term stability of the ambient

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temperature compensation were carried out with fair success. A Radiamatic with sighting tube was located vertically at several distances, varying from 1/16" to 2", above a heated iron bar maintained at 1000°F for periods up to two hours. The ambient temperature near the cold junction was measured by placing an iron-constantan thermocouple in a hole in the thermopile holder. This location allowed temperature measurements to be taken about 1/8" from the compensation coil.

The output of the Radiamatic was continuously recorded on an ElectroniK strip chart recorder. Ambient temperature readings were obtained by measuring the output of the iron-Constantan thermocouple embedded in the Radiamatic.

Radiamatic output was correlated to the temperature of the bar at intervals corresponding to the times at which ambient temperature was taken. During these tests the temperature of the shell rose from an initial ambient temperature of about 85°F to an average of 150°F (with an extreme of 175°F in one case) in half an hour and remained essentially constant thereafter. During this period of time, the Radiamatic output (converted to °F from millivolts) rose 10° to 15° above the original temperature indication within 4 minutes, remained at this level about 10 minutes, and gradually lowered to about 3° to 5°F above the original temperature

when the shell attained equiblibrium temperature.

The rise in the indicated temperature is ascribed to radiation from the hot sighting tube with the eventual drop due to the temperature compensation. The final offset is probably due to the fact that the tip of the sighting tube is warmer than the housing.

Radiamatic Lens and Cone of Sight

The lens of the Radiamatic is made of synthetic calcium fluoride (fluorite) and has a focal length slightly longer than 1-1/6" for monochromatic light of the wavelength of the sodium "D" line. This focal length decreases to about 13/16" for monochromatic light of a wavelength of 8.840^1 microns. The lens is a simple double-convex lens with an effective diameter of 3/4" and equal curvatures on both faces. It must be considered as a thick lens. The optics of the unmodified Radiamatic consist of this lens and a 0.094" diameter stop located 1.20" from the center of the lens. The thermopile is located about 1/16" behind this stop. In the modified Radiamatic a 5"-long sighting tube is placed into the system which puts an

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[1]Focal length calculated from data on index of refraction obtained in Chemical Rubber Handbook, thick lens formula and the blue print of the lens. Other numerical data obtained from blue prints of various parts and assemblies. Distances are nominal.

additional 3/8"-diameter stop 4-9/32" in front of the center of the lens.

An experiment was performed to determine the field of view of the miniature Radiamatic equipped with a sighting tube with a 5/16" aperture and to study the effect of coating the interior surface of the sighting tube with various substances. In these tests a number of runs were made using two Radiamatics; one equipped with a sighting tube finished on the interior with a baked, dull black enamel; and the other equipped with a sighting tube which, for some runs, had a thin cadmium plate over copper and for other runs was coated on the inside with a heavy layer of lampblack.

The Radiamatic assembly was mounted on a stand from which a pivoted bar extended. On the bar, a conical coil was mounted coaxial with the Radiamatic assembly; the wide end of the cone facing the instrument. A baffle with a 1/8"-diameter hole was placed 1/4" in front of the coil to produce a collimated beam of rays. During each run, the bar was moved horizontally in 1/16-inch increments in order to scan a horizontal line in front of the Radiamatic which passed through its axis of sight. The Radiamatic output was recorded on a 0-100 microvolt strip-chart recorder. The Radiamatic output as a function of distance from the axis was plotted for each run to indicate the energy distribution across the cone of sight. A typical

curve is shown in Fig. 4. The result was that less than $\frac{1}{2}\%$ of the energy which reached the detector of the Radiamatic fell outside the mechanical limit of the cone of sight as defined by the optics for all three types of sighting tube linings. Therefore, as far as the cone of sight is concerned, the sighting tube lining is immaterial. A 5/16" opening of a sighting tube affixed to a Radiamatic, limits the cone of sight to a half angle of 7°, while a 3/8" opening establishes an angle of $7\frac{1}{2}^{\circ}$. The target diameter is then 9/16" for a 5/16" opening and 10/16" diameter for a 3/8" opening when the target is 1" from the sighting tube aperture. When the sighting tube is 1/4" from the target, these diameters are 3/8" and 7/16", respectively.

Effect of Distance From Target

In order to test the cone of sight determined in the previous experiment, the variation in output with target distance was measured. A $1\frac{1}{2}$-inch steel tube was heated with an internal heater and controlled at $1000^{\circ}F$. The Radiamatic and sighting tube were held horizontal in a jig and pointed at the side of the tube. The distance between the end of the sighting tube and the hot steel bar could be varied, and several runs were made with different type sighting tubes. It was found that there was a slight decrease in Radiamatic output as the target distance was varied from zero to about one inch, a constant value for several inches, and finally a drop when the bar no longer filled the cone of

sight. The initial drop was as much as $40^{\circ}F$ when a sighting tube with
a polished inner surface was used, but a dull finish caused only a
$10^{\circ}F$ or smaller drop. For this reason all sighting tubes were
given an internal coating of dull black enamel. The initial drop
for the polished surface must have been due to internal reflec-
tions which were not present or not noticeable in the cone of
sight experiment.

Effect of Angle of Sight

With the same set-up as above, the effect of angle of sight
on output was investigated. It was possible to obtain angles as
great as 45° from the vertical and no variation in output could be
noted.

V. EMITTANCE OF URANIUM AS ROLLED AND EMISSIVITY OF THE METAL

A. Introduction - Theory and Definitions[1]

In order to measure the temperature of a surface by optical means, it is usually necessary to know the emittance of the surface. Emittance may be defined as the ratio of the rate of emission of radiant energy from the surface under question to that of a blackbody when both are at the same temperature. A blackbody radiates the maximum amount of energy possible at a given temperature; therefore, emittance varies from 0 to 1. The amount of energy radiated by a blackbody per second is:

$$E_{BB} = \sigma T^4$$

where σ is Boltzmann's constant and is equal to 5.673×10^{-12} where E_{BB} is in watts/cm^2 and T is the absolute temperature, $^\circ$K. The energy radiated by any other surface is:

$$E_n = \zeta \sigma T^4$$

where ζ is the emittance. The term emittance is sometimes broken down into more restricted terms such as total emittance, spectral emittance, etc., but we do not need to do this here.

Another term which is often used is emissivity. Emissivity is a property of a material and not a surface.

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[1] Worthing, A. G. and Halliday, D., Heat, New York, John Wiley and Sons, Inc., 1948, p. 438.

It is rather difficult to measure and seldom finds practical value.
It is defined as the ratio of the rate of energy emission of a
material to that of a blackbody when both are at the same temper-
ature. The only practical way to provide a material where the
surface characteristics are unimportant is to polish the surface.
For example, the emissivity of a polished metal may be .05 where-
as the emittance of the same metal with a rough surface may be
.5 or more. A graybody is also of use in this work. A gray-
body may be defined as a surface or device which radiates a
fraction of the energy of a blackbody when the two are at the
same temperature, with the added requirement that the fraction
does not change with temperature. This, in effect, is saying
that a graybody has a constant emittance for all temperatures.

The emittance of the composite body consisting of uranium
coated with a molten salt mixture is effected by the type and
thickness of an ever-present oxide layer, roughness of the
uranium surface, the transparency of the salt coating, the
thickness of the salt coating, and the angle of emission of the
radiant energy. In order that emittance values be reproduced,
it is necessary that the surface conditions be identical to
those under which the emittance values were originally determined.

At the start of this phase of the investigation, a black-
body furnace which had suitable characteristics for miniature

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Radiamatic calibration was not available. While a calibration fur-

nace was being constructed, emittance experiments were being per-

formed to determine the variation in emittance with temperature.

These experiments consisted of making cooling runs on a salt-coated

uranium bar which had a pencil thermocouple placed in a hole drilled

to within 1/16" of the surface on which the Radiamatic was sighted.

This information was plotted and gave a temperature-emf relation-

ship for a particular bar of uranium and a particular Radiamatic.

In order to determine whether or not there was an emittance varia-

tion during the cooling run, a theoretical constant emittance curve

was made to correspond to the experimental curve at a point. If the

experimental curve coincided with the theoretical curve, then the

emittance was constant during the run. On the other hand, if the

curves were not coincident, then the percent change in the emittance

could be determined.

The theoretical or reference curve was determined theoretically

and experimentally for the Radiamatic with a Calcium Fluoride Lens

(RL-1) and published under Brown Specification No. SS-8226-A.

This theoretical curve is a constant emittance or graybody curve.

As was mentioned in the Introduction, the calibration of all

recorders at Fernald are to be standardized to enable Radiamatic

interchangeability. The calibration selected was 2.000 millivolts

at 1300°F. Since Table SS-8226-A was developed for use with Radia-
matics without sighting tubes, the values given must be modified in
order to pass through the point 2.000 MV at 1300. A complete cali-
bration for the 300°F-1300°F recorder is shown in Table 1 *
while a portion of the same data is plotted in Fig. 5.

One of the most important problems of this investigation was
the determination of a method of measuring the uranium surface
temperatures. It was established, both in the laboratory and in
the field, that the most accurate and reliable means of measuring
the surface temperature was to locate a pencil thermocouple[1] directly
beneath the surface. Results indicated that, if the thermocouple
was within 1/16" of the surface, the error incurred was about 2°F
which amounts to 0.2% at 1000°F. This conclusion was reached after
experimentation using various techniques along with the results ob-
tained on cooling runs with uranium ingots where both the core
temperatures and surface temperatures (measured 1/16" below the
surface) were recorded simultaneously. A typical run on a 3" test
bar indicated that the core temperatures and surface temperatures
were within 10 F of each other throughout the entire run. Hence,

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[1]The pencil thermocuple employed was an iron-Constantan couple about
1/8" in diameter. The 1/8" tube is made of iron with an insulated
Constantan wire mounted coaxially with the tube. One end of the wire
is welded to the tube forming the hot junction of the thermocouple.
The iron tube is chromium plated for corrosion protection.

*See Appendix P. 48   - 20 -

the large temperature gradient must exist across the salt-to-air layer on the uranium surface. This agrees with theory as well as the experimental results obtained while investigating various means of measuring surface temperatures.

Surface Temperature Measuring Techniques

The first attempt at surface temperature measurement employed a contact thermocouple arrangement in which the junction of an 18-gage iron-Constantan, butt-welded thermocouple was flattened and was held against the flat end of a uranium bar by a spring steel arrangement. The spring apparatus was located about three inches from the hot junction which prevented excessive dissipation of heat from the thermocouple hot junction.

Experiment established that the temperature measurements, using the contact thermocouple technique, were about 100°F lower than the actual temperature at about 1100°F. This discrepancy was attributed to several causes, such as heat loss through the thermocouple leads, poor contact with the surface (oxide formed under the hot junction), and dissipation of heat caused by the relatively large thermocouple hot junction. This technique was considered useless for experimental purposes.

A second method for temperature measurement was devised which employed very small thermocouples held in contact with the surface.

A #40 gage Chromel and Constantan thermocouple was held in close contact with a uranium bar by wrapping the lead around the bar. A device consisting of a spring steel "horseshoe" with thermocouple stretched between the two ends and arranged so that the hot junction of the thermocouple was located midway between the two ends was also used to hold the thermocouple on the uranium bar.

Experiments, using this technique, indicated relatively good results since the measured temperature was only about $10^\circ F$-$15^\circ F$ lower than the actual temperature. The reference for this comparison was the freezing point of the salt coating which was $917^\circ F$. This technique was not practical, however, because the small, 0.003-inch diameter, wires were extremely fragile and frequently broke.

A third method of surface temperature measurement consisted of embedding a butt-welded thermocouple in the surface or uranium bars. A slot was machined in the surface to accommodate a No. 18 gage thermocouple and the thermocouple was held in place by peening the edges of the slot. Temperature measurements using this technique were about 15°-$20^\circ F$ below the true temperature at $900^\circ F$.

A No. 30 gage thermocouple was then employed but showed only a slight improvement in the accuracy of the temperature measurements. Because this arrangement was fragile and the anticipated

experimental use of the thermocouple would be considerable, the search for an adequate surface temperature measurement technique continued.

A final method, which provided the required durability, as well as accuracy, consisted of inserting a pencil thermocouple in a drilled hole in the uranium bar. This hole was drilled to within a fraction of an inch of the surface of the uranium. Experimentation established that the temperature about 1/16" below the surface was about 2°F lower than the surface temperature when the surface temperature was 1000°F.

For the purpose of relating the experimental aspects of this investigation easily, individual experiments are reported. Each of the following reports represents the culimination of a series of experiments concerned with a particular subject.

B. Emittance Experiments

Experiment UE-1 – Experimental and Theoretical Temperature-EMF Curve Comparison

Purpose. These experiments are designed to yield a temperature-emf comparison between experimental curves and the theoretical curve.

Description. A 1/8" hole was drilled from one side to within 1/16" of the other side of a 1 1/4" bar of uranium about 8" long.

An iron-Constantan pencil thermocouple, 1/8" in diameter was inserted and seated firmly in the hole and clamped to preserve its position. The bar was permanently mounted on brackets to minimize contact with surrounding surfaces. After the bar was machined to a bright smooth surface and de-greased with carbon tetrachloride, it was placed in the salt bath and heated for 20 minutes to about 1225°F. The bar was then removed from the bath and allowed to cool while a Radiamatic was sighted upon the surface under which the thermocouple was mounted. The Radiamatic sighting tube was located 1/4" from the surface of the uranium. Seven different Radiamatics were used in the test.

Data. See Table No. 2, Appendix, pages 50 and 51.

Results. The results of one run are plotted in Fig. 6. A theoretical curve is also shown. From the curves, it is apparent that the emittance of the salt-coated uranium bar does not change appreciably between 900° and 1200°F since the theoretical curve is followed quite closely. The maximum deviation in any of the seven runs was about 15°-20°F usually at the low end of the range where the salt froze. The surface conditions for these runs are as follows. Initially, the bar was machined smooth and then placed in the salt bath. After each run, the bar was replaced in the bath and reheated. After removal from the salt bath, the bar had a moderate coating of salt which, when frozen, was grayish-black. Although the magnitude

of the oxide layer increased slightly with successive runs, no

appreciable deviations from the constant emittance curves were

noted. The slight increase in the thickness of the oxide undoubted-

ly affected the output of the Radiamatics; but, since different

Radiamatics were employed for each run, a comparison was impossible.

Subsequent attention was given to the effects of oxide and salt

thickness on the Radiamatic output.

Experiment UE-2 - Effect of Oxide Layer on Radiamatic Output

Purpose. To determine qualitatively the effect of oxide on a

salt-coated uranium bar.

Description. Two 1/8" holes were drilled in a 1 1/4" uranium

bar to within 1/16" of the surface as before. Two iron-Constantan

pencil thermocouples were inserted and mounted permanently in the

holes. The bar was about 9" long with the holes located 1/3 the

distance from each end. One-half of the surface of the bar was

machined leaving the other half oxide-salt coated. Brackets

prevented the uranium from coming in contact with surrounding

surfaces. Two Radiamatics were arranged such that one sighted

on the machined surface while the other sighted on the oxide

surface; both were mounted 1/4" from the surfaces under which the

thermocouples were mounted. The Radiamatics were calibrated identi-

cally by having both sighted on a homogeneous surface of a uranium

bar at constant temperature. One Radiamatic was equipped with a potential divider and its output was adjusted so that it was equal to the output of the other.

With the Radiamatic outputs and the uranium surface temperatures recording automatically, it was possible to determine the effect of the surface condition on the Radiamatic output when the bar was heated and then allowed to cool.

Results. Fig 7 shows the outputs of the two Radiamatics as a function of time during a run. It can be seen that the output of the Radiamatic sighted on the machined surface is considerably greater than that of the other Radiamatic at high temperatures. Fig. 8 shows the output vs. temperature for the two Radiamatics plus a theoretical curve. It is seen that the Radimatic sighted on the machined surface follows the theoretical curve quite well, while the other departs slightly at elevated temperatures. The change in slope of the curves in Fig. 7 is due to the β to α phase change in the uranium.

The difference in output between the machined surface (which was lightly oxidized) and the thickly oxidized surface is not readily explained when later experiments are considered. Some of the difference may have been due to an insulating effect caused by the oxide and some due to error in temperature measurement.

Experiment UE-3 - Effect of the Oxide-Salt Layer on Radiamatic Output

Purpose. To determine quantitatively the effect of the oxide-salt layer of uranium on Radiamatic output.

Description. In Experiment UE-2, a 25°F temperature difference was noted between the Radiamatic output for the machined surface as compared to the output from the heavily oxidized surface. This oxide-salt-coated surface was the surface that the bar possessed after being rolled plus additional oxide and salt from the laboratory salt bath. In order to study the effect of an increasing oxide-salt layer on the Radiamatic output, a 3" diameter by 7" bar of uranium was machined over its entire surface. Two holes were drilled as before and thermocouples inserted. The thermocouples were located 1/3 the distance from each end of the test bar. A Radiamatic was arranged so that it could sight the surface above one thermocouple and then move horizontally in order to sight on the surface above the other thermocouple. The outputs of the thermocouples and Radiamatic were automatically recorded.

One important modification in the experimental set-up should be noted. Instead of mounting the thermocouples permanently in the bar of uranium, as was done in Experiment UE-2, the thermocouples were inserted in the holes after the bar was removed from the salt bath and then withdrawn after each cooling run. Tension was maintained

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manually on the thermocouples to assure metal-to-metal contact in the holes. This technique was adopted for two reasons. First, the positions of the thermocouples were able to be reproduced thereby assuring reproducible temperature measurements. Gross errors were noted if the thermocouples were not in contact with the uranium. Secondly, the thermocouples were severly damaged because of repeated shocks when heated with the uranium bar in the salt bath.

A long series of tests were made on the bar. On the first run, the Radiamatic was sighted over one thermocouple and a record of output and temperature was recorded. The surface over the other thermocouple was wiped with a piece of asbestos cloth while the run was under way. The bar was reheated and a second run made recording the Radiamatic output and temperature on the surface which was wiped during the first run. The procedure above was followed for 21 runs. The surface which was wiped every other run remained relatively smooth. At first, a thin layer of oxide formed but it never got very thick. The unwiped surface built up a rather thick oxide layer after several hours spent in the bath.

Data. See Table 3, Appendix, pages 52, 53 and 54

Results. The results show that for the amount of oxide which formed in the bath there is no variation in emittance between the

"clean" and the oxidized surface. A more important result is illustrated by Table 4. The average Radiamatic output, the probable error, the theoretical output from a blackbody and the emittance are tabulated in Table 4. The probable error is defined as:

$$R = .6745 \, \sigma$$

where σ is the standard deviation which is the root mean square of the actual deviations. The emittance values fall very close to each other at all temperatures from 900°F to 1200°F and the value of .865 $\neq$ .01 appears to be a good value. It must be mentioned that the emittance value given above is determined using as a reference point an experimental value for the Radiamatic output where sighted at a blackbody. This reference point was obtained with a small blackbody furnace designed for this project. and will be discussed later. The accuracy of the value of emittance found depends directly on the accuracy of the black-body furnace.

Experiment UE-4 - Effect of Salt Thickness on Radiamatic Output

Purpose. To determine quantitatively the output of the Radiamatic as a function of the thickness of the salt layer.

Description. In order to study the emittance of the salt independent of the uranium, a substance having a somewhat lower emittance than the salt, was employed as a receptacle for the molten salt. The receptacle used was an aluminum bar, 1 inch in diameter and 1 3/4 inches long. One end of the bar was recessed to a depth of about 1/16 inch leaving a ridge along the circumference. A hole was drilled into the center of the rod to within 1/16 inch of the recessed end. A pencil thermocouple was forced into this hole and provided a means of support for the bar. Insulating tape was wrapped around the aluminum slug over which a heater winding was placed. The heating element could raise the temperature to 1200°F. A Radiamatic was mounted directly over the recess and its sighting tube was lowered to within 1/4 inch of the recessed surface. The temperature was recorded and controlled by means of the thermocouple and a strip chart recorder-controller.

Before investigating the emittance of the salt, the emittance of the machined aluminum surface was determined for various temperatures. Salt was then placed on the aluminum surface and its thickness was determined.

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Various means of measuring the salt thickness were employed. The first method was to freeze the salt and then remove or chip a sample of the salt from the surface for measurement. This was unsatisfactory because of the roughness of the surface which results in sampling only a portion of the layer. Another method was to compare the thickness of the layer with a suitable standard. This method had the disadvantage of requiring considerable time for each measurement which was not warranted since the accuracy of the measurement was not any greater than the accuracy for the wire method. The wire method was that which was finally used in this experiment, not only for its accuracy but for its simplicity. A steel wire, No. 22 gage, was cut and cleaned with emery paper using the same technique for each measurement. The wire was inserted perpendicularly into the salt until it rested against the aluminum surface. After removing the wire and permitting the salt that adhered to the surface to freeze, an eye piece comparator was employed which was capable of measuring to within $\pm$ 0.005 of an inch. It was determined that the wire should remain in the salt a sufficient length of time for the wire to reach the salt temperature.

The temperature control cycle for the bar did not cause difficulty in measuring the emittance of the salt since the

Radiamatic output followed these fluctuations closely. All measurements were made at the same point on the control cycle. Errors caused by the temperature gradient between the thermocouple and the salt layer were kept at a minimum by allowing the heater element to extend above the level of the salt which also provided some protection from air currents and drafts.

Because of the conditions encountered at the experimental rollings, the output of the Radiamatic as a function of salt thickness was determined for both clean salt and "dirty" salt. Salt in which black uranium oxide and mill dirt was suspended was considered dirty salt. In order to verify the emittance values obtained, a similar but somewhat abbreviated run was made using a stainless-steel receptacle.

Results. The plot of emittance as a function of salt thickness for clean salt at several temperatures, Fig. 9, indicates that the emittance of the coated aluminum surface increases with an increase in salt thickness. A maximum is reached for thicknesses of 0.085", 0.100", and 0.090" for the temperatures, 900°, 1000°, and 1100°F, respectively. The maximum emittance at 900°F is approximately 0.860; for 1000°F, 0860; and for 1100°F, 0.833. The decreasing emittance with increasing salt thickness is probably caused by the large gradient which may exist across the salt layer at the

higher temperature. If the relationship between the salt-layer temperature and the emittance of the salt were the prime objective, it would have been necessary to establish accurately the rate of change of emittance with increasing salt-layer thickness. This thickness would, of necessity, extend far beyond the limits considered here. By extrapolating this 'cooling' curve to zero thickness, the true emittance of the salt film at the temperature of the bar or salt layer could be determined.[1]

Although this experiment was not intended to accomplish this end, the 'cooling' effect is noticeable. When this curve is extrapolated, the emittances at zero thickness for the three temperatures considered, are probably close to 0.93. However, the emittance for a given salt layer at a certain bar temperature is the information required for this project.

For the case of dirty salt, the plot of the emittance as a function of the salt layer thickness, Fig. 10, indicates maxima between salt thicknesses of 0.025" and 0.030". The maximum emittances at 900°, 1000°F, and 1100°F are 0.875, 0.860, and

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[1] Sully, Brandes, and Waterhouse, Brit. J. of Appl. Phys., 3, p. 97, 1952.

0.860, respectively. By comparison, the dirty salt has emittances slightly higher than those for clean salt films but these differences are so small that they may be neglected.

The important fact is that both clean and dirty salt show a maximum emittance almost equal to the average value of the emittance of salt-coated uranium as determined in Experiment UE-3.

The magnitudes of the emittances were checked using a stainless-steel slug in place of aluminum, and it was found that the values checked rather closely.

Experiment UE-5 - The Emittance of Oxide-Coated Uranium Surfaces at Elevated Temperatures

Purpose. To determine the emittance of uranium at elevated temperatures in the absence of a protective salt film.

Description. The experimental set-up for this experiment was the same as that for Experiment UE-4 except that the metal slug was uranium with a smooth target surface. The heating element was capable of raising the temperature of the uranium to about 1300°F.

Because of the rapid oxidization of the uranium at elevated temperatures, it was necessary to scrape and buff the surface continually to remove the excess oxide. The surface appeared quite smooth despite the relatively thick layer of oxide. The temperature

of the oxide layer was probably lower than the sub-surface temperature of the uranium bar as indicated by the thermocouple. An attempt was made to minimize this difference by mounting the heating coil in such a manner as to provide heat to the surface and the air just above the surface.

The output of the Radiamatic was measured during repeated heating and cooling runs thereby providing numerous measurements over the temperature range considered. Before each reading, the uranium surface was scraped and brushed. This had a tendency to cool the surface; therefore, it was necessary to delay the Radiamatic measurements until the temperature held constant.

Results. Figure 11 shows a curve of emittance as a function of temperature for the bare uranium bar, or actually the emittance of uranium oxide since the bar was always coated with oxide. There appears to be a maximum of about 0.84 at 1025°F; the emittance falls to about 0.80 at 775°F and 1300°F. This variation may not be significant because of the difficulty of obtaining a reproducible surface. However, the fact that the oxide surface has an emittance so close to that of the salt is of great interest. This would indicate that little trouble would be experienced in case the salt were rubbed off during rolling and also that, if rolling

were done without salt, little change in the calibration of the

Radiamatics would be necessary.

Experiment UE-6 - The Emissivity of Uranium

Purpose. To determine the emissivity of uranium metal.

Description. The emissivity of uranium is of interest in that
this characteristic of the metal has not received much attention
by earlier workers. Hale and Wright[1] determined an average emissivity
of 670 mμ of 0.51 while Wahlin[1] calculated an emissivity of .453
at 1050 and .415 at 1052°C. All of these emissivities are at
elevated temperatures and were not thought worth while for the present
work. We concentrated on lower temperatures.

A small vacuum chamber was constructed which would hold a
uranium bar and also a Radiamatic. The uranium bar had a hole
drilled through the center and a heater was placed in the hole.
A 1/8-inch pencil thermocouple was also inserted in the bar and the
surface was polished to a mirror finish. The Radiamatic fitted into
an opening in the side of the vacuum chamber and could be removed
for calibration.

Results. Uranium at elevated temperatures has a strong
affinity for all but the noble gases, and we experienced much

[1]Katz, J.S. and Rabinowitch, E., The Chemistry of Uranium, New York,
McGraw-Hill Book Co., Inc.; 1951; p. 160.

trouble with oxidation of the surface. However, by pumping the chamber as low as possible (100 μ), and by rapid heating it was possible to measure the emissivity out to about 600°F. The value of emissivity obtained from 200 to 600°F was 0.15 ± .03. Above 600°F, the oxidation proceeded too rapidly to determine the emissivity of the unoxidized surface.

Summary of Results

It has been experimentally determined that the emittance of uranium, coated with a eutectic mixture of lithium and potassium carbonates is constant between temperatures of 900°F and 1200°F. The value of emittance obtained is 0.865 ± 0.01. This value of emittance is dependent on the accuracy of a blackbody calibration furnace which is about 1%. The emittance of the molten salt alone is dependent on thickness but an extrapolated value is about 0.9. Dirty salt, that is salt with uranium oxide and steel mill dirt mixed with it, gave an emittance of about 0.86, very close to that of uranium. The emittance of uranium oxidized in air at elevated temperatures falls between 0.80 and 0.84 in the temperature range between 900°F and 1300°F, the uncertainty being caused by the difficulty of obtaining uniform surface conditions due to rapid oxidation. The emissivity of uranium metal was about 0.15 between the temperatures of 200°F and 600°F.

VI. CALIBRATION FURNACE

In order to use the information determined in previous sections it is necessary to have a standard of radiation for calibration purposes. Indeed, the emittance and emissivity measurements depend on a knowledge of the behavior of the test instruments under blackbody conditions. For these two reasons, it was necessary to design and build a calibration furnace for use with the Radiamatics.

A cavity whose walls are all at a uniform temperature is a blackbody cavity. If a small hole is cut into the cavity, the hole will act as a blackbody radiator providing that the loss of energy through the hole is not great enough to disturb the conditions within the cavity. The materials of construction of the blackbody cavity are unimportant since a low emittance material is a good reflector and therefore multiple reflections inside the cavity make up for the lower emittance.

Furnace Design

The furnace required for this work needed to possess several characteristics.

1. A close approximation to a blackbody.

2. Small and portable.

3. Electrically heated.

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4. Usable at least to 1300°F.

5. Temperature measuring means built in.

6. Handy for use with Radiamatic and sighting tube.

The design decided on was quite simple. A metal tube was used as the furnace, a heater winding wrapped around it supplying the power. The furnace core was wrapped in tape insulation and slipped into a ceramic protecting tube and the protecting tube was in turn fitted within a steel shell. The furnace is shown in Figures 12 and 13. In Fig. 12, "A" is the furnace core with two iron-Constantan pencil thermocouples inserted in one end; "B" is a ceramic protecting tube to con - tain the core and its heaters; "C" shows three Transite discs which hold the Radiamatic sighting tube during calibration and act as a baffle for the core; and "D" is a stainless steel outer housing with two large Transite discs to close the two ends. Fig. 13 "A" shows the core with its heater winding in place and "B" shows the completed furnace.

The furnace core is built from a piece of stainless steel rod $6\frac{1}{2}$ inches long and 1.725 inches in diameter. A hole, 1.109 inches in diameter and 5 1/4 inches deep, was drilled in one end and another hole, 1.109 inches in diameter and 1 inch deep, was drilled in the other end. The large hole formed the blackbody cavity. Two 1/8-inch iron-Constantan thermocouples were inserted into holes drilled into the back end of the core. The heater winding was made in three parts, one

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extending the full length of the tube, one covering the first two
inches, and the third covering the last two inches. The long winding
was 32 ohms, 380 watts; while the two equal auxiliary heaters in
series were 44 ohms, 280 watts; the total power input being about 660
watts at 110 volts. Tophet[1] C #26 gage wire was used. Refrasil[2] tape
was used to insulate the core and the windings. This insulation tape
is a good insulator up to about 2000°F and works well in the furnace.
The ceramic protecting tube was built from a silicon carbide thermo-
couple protection tube and worked satisfactorily. The Transite discs
which support the Radiamatic sighting tube were cemented into the silicon
carbide tube and no case of loosening was ever encountered. The end
discs and the rings around the tube were held in place by means of self-
tapping screws through the stainless steel outer container.

Furnace Performance

Two early models of the furnace were made before the final design
was established. They were almost the same as the final design and were

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[1] Tophet C is manufactured by the Wilbur B. Driver Co., Newark,
New Jersey.

[2] Refrasil is manufactured by the H. I. Thompson Co., Los Angeles,
California

equipped with means for measuring the temperature throughout the core.

At first, before the two auxiliary windings were used, the temperature dropped off greatly near the ends of the core. However, with power applied to the end heaters, a reasonably flat gradient was obtained. The control for the furnace was a simple on-off control which produced a control cycle of $\pm\ 2^{\circ}F$ with a 1 1/4-minute period. A plot of the temperature from one end of the core to the other is shown in Fig. 14. It can be seen that the temperature gradient is quite small and that the cavity surface is almost isothermal. A series of points of Radiamatic output vs. temperature of the furnace with a theoretical curve is shown in Fig. 15. This indicates that the furnace is almost an ideal blackbody and that the maximum error is using it as a blackbody probably does not exceed 10 or $15^{\circ}F$. Five different furnaces were built during the project and they all gave identical results under identical conditions to within 1%. This indicates that the furnace makes a good reference for both emittance studies and calibration.

VII. THE RADIAMATIC CALIBRATION PANEL

Introduction

It was early recognized that a calibration means would be needed
for the application of this optical method of temperature measurement.
The calibrating furnace described in the previous section was designed
for this end. The furnace could be easily used to calibrate receivers
in the laboratory where trained personnel were available to make the
necessary calculations which, while not complicated, require a knowledge
of the theory behind the procedure. The search for an answer to the
problem of an easy means for calibration led to the development of a
piece of equipment called the Radiamatic calibration panel.

Panel

The front and the back of the calibration panel are shown in
Figures 16 and 17. The panel consists of three primary components,
a 300°F to 1300°F strip-chart recorder calibrated for a miniature
Radiamatic with 2.000 MV equal to 1300°F, a 700°F to 1300°F on-off
front-set recorder-controller and the blackbody furnace. There are
also several minor elements, switches, pilot lights, a terminal block,
a calibration curve, and others. The method of use of the panel is
quite simple. Fig. 18 shows a close up of the 700°F to 1300°F
recorder-controller. The setpoint of the controller is at 950°F and

the recorder pen indicates that the furnace temperature is being controlled at this temperature. The glass tearoff strip on this recorder has been replaced by a plastic strip with a second scale engraved on it. It can be seen that this scale does not agree with the instrument scale. The difference is caused by the fact that uranium, for which the scale was calculated, has an emittance of about 0.86.

Calibration Procedure

It is seen that the recorded record of furnace temperature passes under the second scale at 1000°F. This means that, if a Radiamatic is connected to the upper recorder and inserted in the furnace, the Radiamatic recorder should read 1000°F. If it does not, the receiver is out of calibration and the calibrating potentiometer should be readjusted. This procedure makes calibration very simple for no knowledge of the emittance is required in order to calibrate the receiver. In addition, if it is desired to calibrate the receiver for use with some other material, all that is needed is a new tear-off strip with the proper scale.

Preparation of Scale

The preparation of the calibration scale requires that the emittance of the material used be known, plus the calibration curve

of the Radiamatic recorder. If the object had an imittance of 1.0,
it would be a blackbody and the calibration scale would be identical
to the 700°F to 1300°F recorder scale. For a material with an
emittance less than 1.0, the calibration scale will always read
higher than the recorder scale. The easiest way to illustrate the
method of preparing a calibration scale is to work an example. Fig. 19
shows two curves, Curve A is the Radiamatic calibration curve and passes
through the point 2 millivolts at 1300°F. This is the calibration curve
of the upper recorder on the panel. Curve B is calculated from Curve A
using the emittance of the material, 0.86 in the case of uranium.
Point (b), for example, is determined by multiplying the millivolts
value at point (a) by the emittance, 0.86, and indicates that a radia-
tion receiver pointed at a piece of uranium will have an output 0.86
times that of one pointed at a blackbody radiation. The remainder of
Curve B is found in the same manner.

In order to determine the calibration curve for the tear-off
strip the following procedure is used. Pick a temperature (a) which
will be the furnace temperature, and follow a horizontal line to
point (c). This is the Radiamatic output when calibrated for a
blackbody. Next, move vertically to point (d) which is on curve B and
from (d) over to (e) which gives the calibration temperature for one

point. This procedure may be repeated to give other points on the scale. It may be desirable to reverse the procedure to give even values of scale temperatures but this is up to the user.

If the emittance of the object varies with temperature, the same procedure may be used and the results will allow calibration of the Radiamatic in the temperature range where it will be used. The calibration will be in error at other temperatures, however.

Errors

The error of calibration depends on many factors such as the error in the determination of the emittance, the recorder errors, the error in setting the calibration potentiometer and several others which might enter. In no case was the error more than about 2% in practice and this figure is probably the smallest error that the method can produce. The error, however, is constant; that is, it does not change much under different conditions so that operating experience should allow reproducible results somewhat better than 2%.

VIII. CONCLUSION

The equipment designed and built on this project has not yet been extensively tested in the field. The results of the work at the experimental rollings is on record at the New York Operations Office and much information on actual rolling conditions along with some of the solutions to various problems may be found there. It is expected that a report will be issued by National Lead of Ohio sometime in the future, covering operational experience with the equipment.

A P P E N D I X

Table No. 1. Radiamatic Recorder Calibration Curve* or Theoretical Curve Temperature vs. E.M.F.

Temp. °F	Milli-volts	Temp. °F	Milli-volts	Temp. °F	Milli-volts	Temp. °F	Milli-volts	Temp. °F	Milli-volts
200	0.010	680	0.285	1160	1.404	1640	4.191	2120	9.698
220	0.014	700	0.310	1180	1.481	1660	4.361	2140	10.01
240	0.017	720	0.336	1200	1.560	1680	4.536	2160	10.32
260	0.021	740	0.364	1220	1.643	1700	4.715	2180	10.64
280	0.026	760	0.393	1240	1.728	1720	4.899	2200	10.97
300	0.031	780	0.424	1260	1.816	1740	5.087	2220	11.31
320	0.037	800	0.457	1280	1.906	1760	5.286	2240	11.65
340	0.043	820	0.492	1300	2.000	1780	5.477	2260	12.01
360	0.050	840	0.566	1320	2.097	1800	5.680	2280	12.37
380	0.058	860	0.566	1340	2.197	1820	5.888	2300	12.73
400	0.067	880	0.606	1360	2.301	1840	6.100	2320	13.11
420	0.076	900	0.647	1380	2.411	1860	6.318	2340	13.50
440	0.086	920	0.691	1400	2.528	1880	6.542	2360	13.89
460	0.097	940	0.737	1420	2.648	1900	6.771	2380	14.30
480	0.108	960	0.785	1440	2.769	1920	7.006	2400	14.71
500	0.121	980	0.836	1460	2.894	1940	7.242	2420	15.13
520	0.135	1000	0.889	1480	3.021	1960	7.493	2440	15.56
540	0.150	1020	0.944	1500	3.155	1980	7.745	2460	16.00
560	0.165	1040	1.001	1520	3.291	2000	8.004	2480	16.45
580	0.182	1060	1.060	1540	3.430	2020	8.269	2500	16.91
600	0.206	1080	1.123	1560	3.572	2040	8.541	2520	17.36
620	0.220	1100	1.189	1580	3.718	2060	8.819	2540	17.82
640	0.241	1120	1.260	1600	3.876	2080	9.105	2560	18.27
660	0.263	1140	1.330	1620	4.026	2100	9.397	2580	18.72

Table No. 1 continued

Temp. °F	Milli-volts	Temp. °F	Milli-volts
2600	19.18	2960	29.79
2620	19.69	2980	30.41
2640	20.20	3000	31.04
2660	20.71	3020	32.28
2680	21.28	3040	32.40
2700	21.84	3060	33.08
2720	22.41	3080	33.76
2740	22.98	3100	34.44
2760	23.55	3120	35.12
2780	24.17	3140	35.80
2800	24.79	3160	36.48
2820	25.42	3180	37.16
2840	26.04	3200	37.84
2860	26.67	3220	38.52
2880	27.29	3240	39.26
2900	27.91	3260	40.00
2920	28.54	3280	40.74
2940	29.16	3300	41.48

*These data were calculated from M-H Brown Specification No. SS-8226A, a theoretical constant emmitance curve, using 2.000 M.V. at 1300°F as a reference point. These data are for Radiamatics equipped with a Calcium Fluoride Lens (RL-1) based on a 110°F housing temperature.

Table 2. Temperature vs. E.M.F. - Theoretical Curve Comparison

Radiamatic II - 13		Radiamatic III - 3		Radiamatic IV - 2	
M.V.	Temp. (°F T/C)	M.V.	Temp. (°F T/C)	M.V.	Temp. (°F T/C)
3.21	1194	2.36	1212	1.88	1197
---	1199	2.21	1189	1.67	1165
3.08	1192	2.01	1156	1.53	1130
2.89	1157	1.84	1123	1.39	1099
2.62	1132	1.68	1092	1.28	1069
2.54	1108	1.54	1062	1.18	1040
2.33	1080	1.41	1033	1.09	1012
2.11	1052	1.30	1005	1.00	985
1.94	1022	1.20	977	0.93	959
1.75	995	1.11	951	0.86	934
1.65	969	1.04	926	0.80	911
1.49	944	0.95	904	0.73	889
1.38	920	0.89	882	0.68	868
1.24	899	0.81	861	0.62	848
1.17	878	0.74	842	0.57	829
1.06	858	0.69	824	0.53	811
0.995	838	0.65	806	0.49	794
0.91	819				
0.86	802				
C. F.[1] = 2.025		C. F.[1] = 1.434		C. F.[1] = 1.178	

[1]C.F. is the conversion factor for the theoretical curve
(C. F. x Theoretical E.M.F.'s = Theoretical).

Table 2. continued

Radiamatic V-5		Radiamatic VI-6		Radiamatic VII-7		Radiamatic VIII-8	
M.V.	Temp. ($^{\circ}$F T/C)	M.V.	Temp. ($^{\circ}$F T/C)	M.V.	Temp. ($^{\circ}$F T/C)	M.V.	Temp. ($^{\circ}$F T/C)
2.16	1159	1.88	1151	2.23	1131	1.90	1155
1.97	1123	1.68	1116	2.02	1097	1.71	1120
1.80	1090	1.53	1083	1.85	1064	1.56	1087
1.65	1059	1.42	1052	1.70	1033	1.42	1056
1.51	1028	1.29	1023	1.55	1005	1.34	1027
1.40	1001	1.20	995	1.44	977	1.21	998
1.28	973	1.11	968	1.33	951	1.13	970
1.21	948	1.02	943	1.22	926	1.03	944
1.11	924	0.94	919	1.12	903	0.97	920
1.02	901	0.88	897	1.03	881	0.89	897
0.95	881	0.81	875	0.94	860	0.81	876
0.88	859	0.76	853	0.88	840	0.74	855
0.82	841	0.70	833	0.82	822	0.69	835
0.76	823	0.65	815	0.76	804	0.63	816
0.72	805	0.61	799			0.59	799
C. F.[1]= 1.564		C. F.[1] = 1.361		C. F.[1] = 1.721		C. F.[1] = 1.372	

[1]C.F. is the conversion factor for the theoretical curve
(C. F. x Theoretical E.M.F.'s = Theoretical).

Experiment UB-3

Table 3. Temperature vs. E.M.F. for Salt-Coated Uranium Bars

Millivolt Output   Bar No. 1

Temp. °F	Run 1	Run 2	Run 2(w)	Run 3	Run 4	Run 4(w)	Run 5	Run 6-6(w)	Run 7	Run 8
900	---	0.700	0.708	0.695	0.710	0.700	0.696	0.710	0.650	0.678
925	---	0.763	0.763	0.753	0.763	0.755	0.750	0.761	0.722	0.732
950	0.807	0.825	0.825	0.818	0.822	0.813	0.809	0.818	0.793	0.794
975	0.873	0.892	0.890	0.887	0.886	0.880	0.875	0.880	0.863	0.858
1000	0.941	0.962	0.960	0.960	0.958	0.953	0.946	0.950	0.935	0.930
1025	1.010	1.038	1.032	1.033	1.036	1.030	1.025	1.025	1.004	1.003
1050	1.080	1.118	1.107	1.108	1.120	1.110	1.107	1.111	1.085	1.082
1075	1.160	1.195	1.180	1.192	1.203	1.190	1.189	1.196	1.172	1.162
1100	1.242	1.278	---	1.280	1.287	1.275	1.275	1.282	1.278	1.245
1125	1.34	1.365	---	1.37	1.372	1.355	1.362	1.374	1.398	1.340
1150	1.465	1.465	---	1.465	1.460	---	1.447	1.470	---	1.453
1175	---	---	---	---	---	---	---	---	---	---

Table 3 continued

Experiment UM-3

Millivolt Output

Temp. °F	Bar No. 1							Bar No. 2		
	Run 8(w)	Run 9	Run 10	Run 10(w)	Run 11	Run 12	Run 12(w)	Run 13	Run 14	Run 14(w)
900	0.688	0.653	0.665	0.690	0.683	0.671	0.693	0.698	0.682	---
925	0.745	0.717	0.725	0.748	0.738	0.737	0.748	0.763	0.747	0.755
950	0.806	0.783	0.788	0.803	0.795	0.800	0.808	0.829	0.810	0.816
975	0.873	0.851	0.853	0.865	0.860	0.866	0.875	0.897	0.880	0.882
1000	0.940	0.918	0.919	0.935	0.930	0.935	0.945	0.968	0.950	0.952
1025	1.013	0.987	0.988	1.088	1.000	1.002	1.015	1.039	1.019	1.023
1050	1.090	1.057	1.065	1.083	1.073	1.075	1.088	1.118	1.093	1.101
1075	1.170	1.140	1.145	1.162	1.154	1.159	1.166	1.200	1.175	1.183
1100	1.255	1.227	1.232	1.241	1.245	1.245	1.250	1.283	1.265	1.270
1125	1.340	1.327	1.322	1.322	1.352	1.340	1.350	1.375	1.360	1.360
1150	---	1.422	1.407	---	---	1.450	1.472	1.466	1.459	1.468
1175	---	---	---	---	---	---	---	1.558	1.557	1.583
1200	---	---	---	---	---	---	---	---	1.659	1.674

Table 3 continued.　　　　　　**Experiment UE-3**

Millivolt Output

									Bar No. 2	
Temp. °F	Run 15	Run 16	Run 16(w)	Run 17	Run 18	Run 18(w)	Run 19	Run 21	Run 21(w)	Run 22
900	0.705	0.687	0.67	0.672	0.703	0.703	0.699	0.685	0.697	0.700
925	0.760	0.750	0.750	0.740	0.765	0.769	0.752	0.750	0.755	0.760
950	0.820	0.811	0.811	0.800	0.830	0.835	0.813	0.816	0.820	0.825
975	0.888	0.877	0.877	0.863	0.898	0.902	0.880	0.884	0.890	0.893
1000	0.960	0.942	0.942	0.935	0.968	0.973	0.951	0.953	0.963	0.958
1025	1.035	1.018	1.018	1.002	1.044	1.051	1.024	1.027	1.038	1.028
1050	1.116	1.095	1.100	1.078	1.122	1.134	1.099	1.105	1.116	1.102
1075	1.197	1.179	1.183	1.151	1.203	1.219	1.184	1.183	1.202	1.179
1100	1.278	1.266	1.274	1.239	1.287	1.305	1.267	1.275	1.291	1.265
1125	1.360	1.350	1.362	1.330	1.380	1.397	1.355	1.366	1.383	1.357
1150	1.450	1.440	1.459	1.421	1.475	1.490	---	1.460	1.478	1.450
1175	1.553	1.533	1.555	1.515	1.570	1.493	---	1.561	1.585	1.550
1200	1.674	1.628	1.652	1.618	1.685	1.695	---	1.676	1.694	1.660

Table No. 4. Emittance vs. Temperature for Salt-Coated
Uranium Bars

Temperature °F	Radiamatic Output, Mv for U Bar	Theoretical Radiamatic Output, Mv for Blackbody	Emittance	Probable Error
				$\not=$
900	0.687	0.795	0.864	0.016
925	0.747	0.862	0.867	0.013
950	0.810	0.937	0.867	0.012
975	0.876	1.011	0.866	0.011
1000	0.946	1.092	0.866	0.010
1025	1.018	1.171	0.869	0.009
1050	1.096	1.264	0.867	0.011
1075	1.177	1.364	0.863	0.010
1100	1.264	1.461	0.865	0.009
1125	1.357	1.574	0.862	0.009
1150	1.451	1.689	0.859	0.008
1175	1.550	1.805	0.859	0.007
1200	1.657	1.916	0.865	0.009
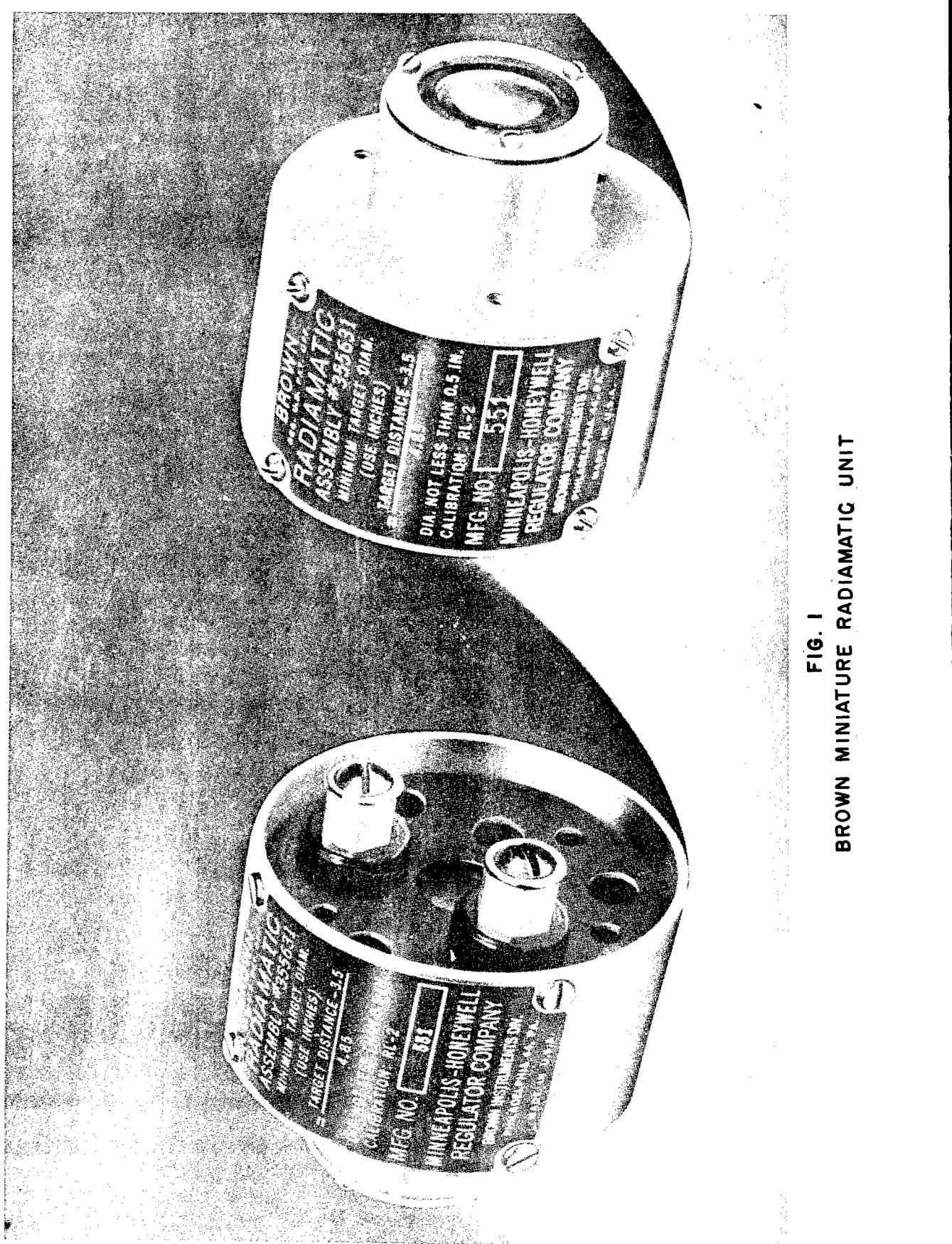
FIG. I

BROWN MINIATURE RADIAMATIC UNIT
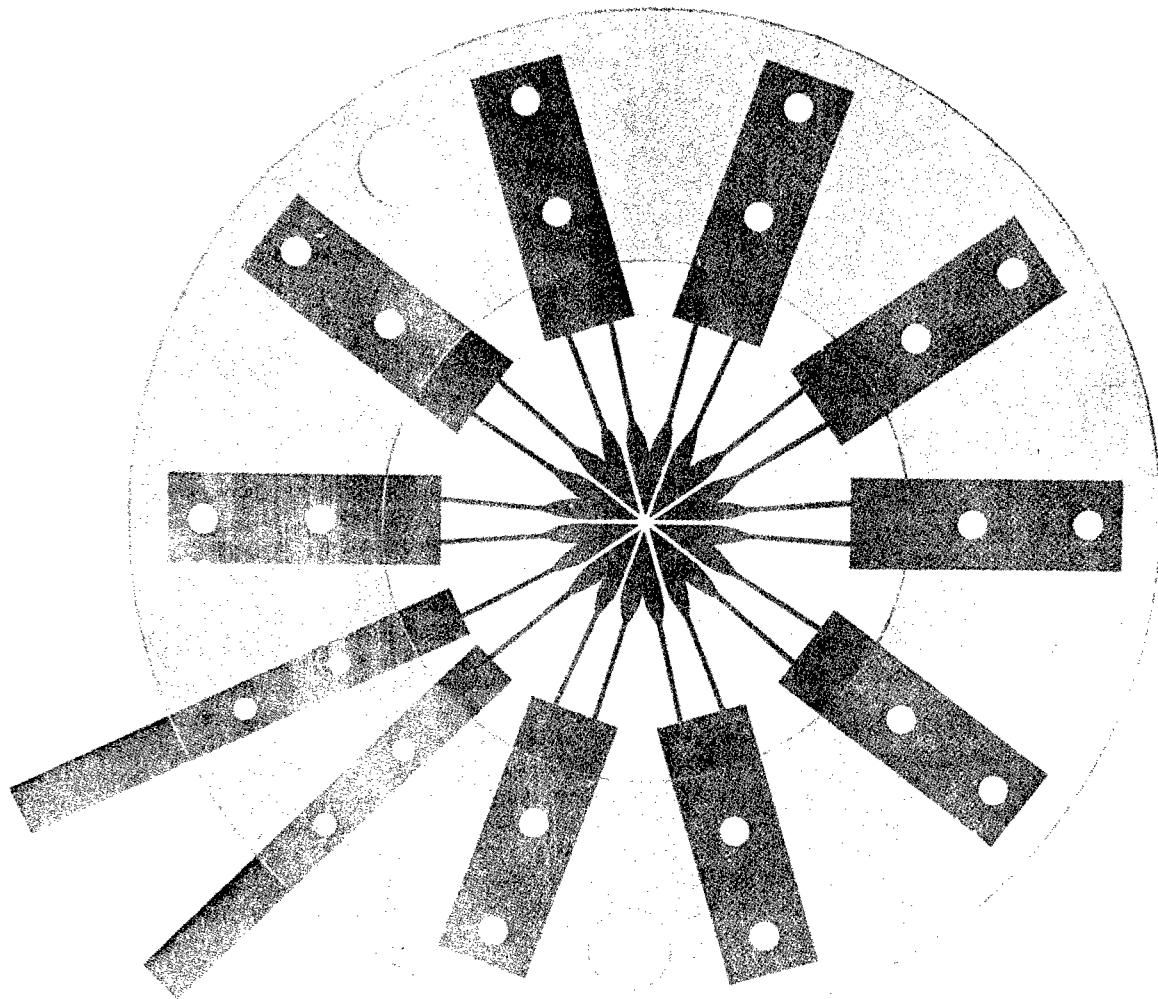
FIG. 2
RADIAMATIC THERMOPILE

- 57 -
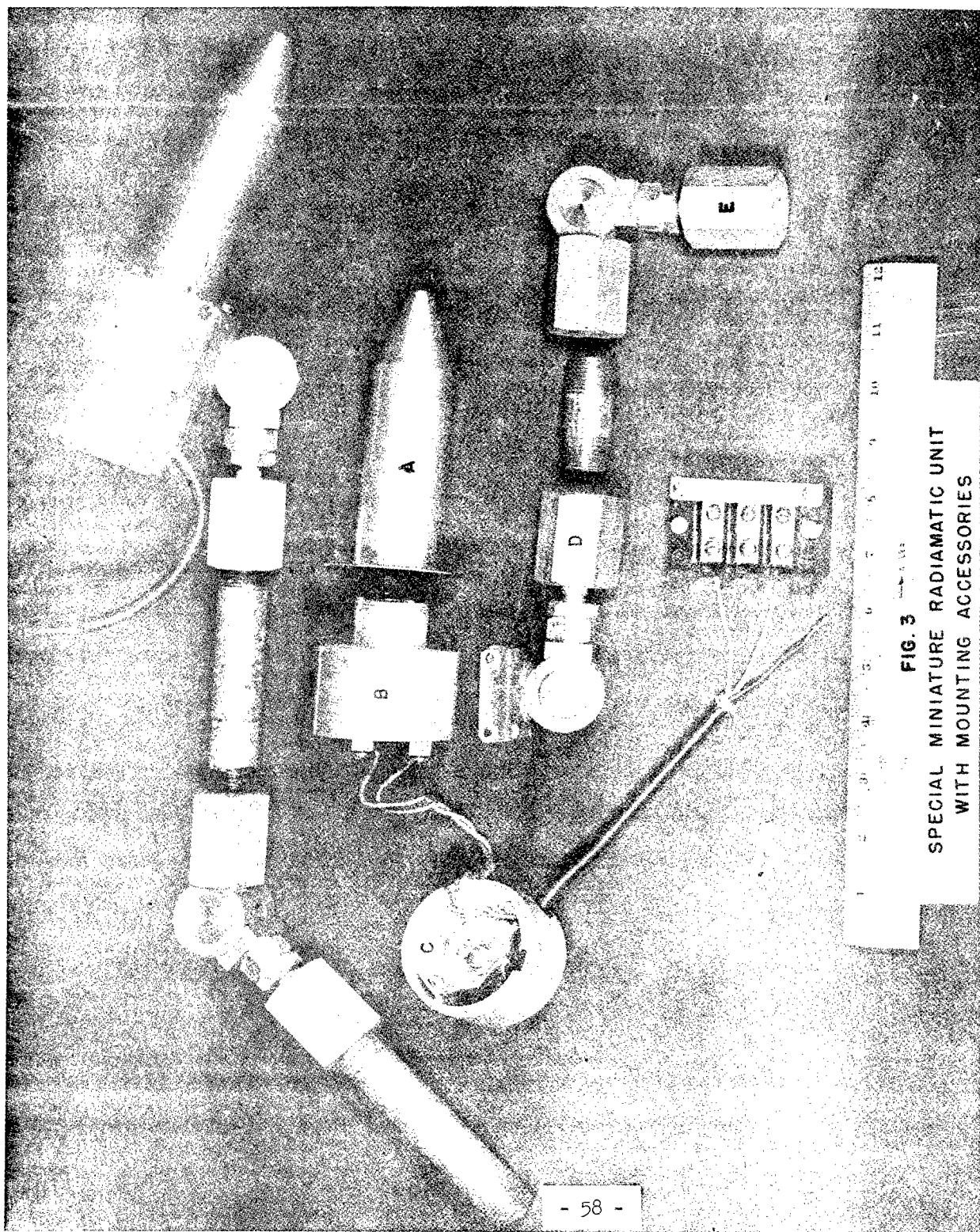
FIG. 3

SPECIAL MINIATURE RADIAMATIC UNIT
WITH MOUNTING ACCESSORIES

Radiamatic Receiver with Sighting Tube Output as a Function on Angle Off Center Line
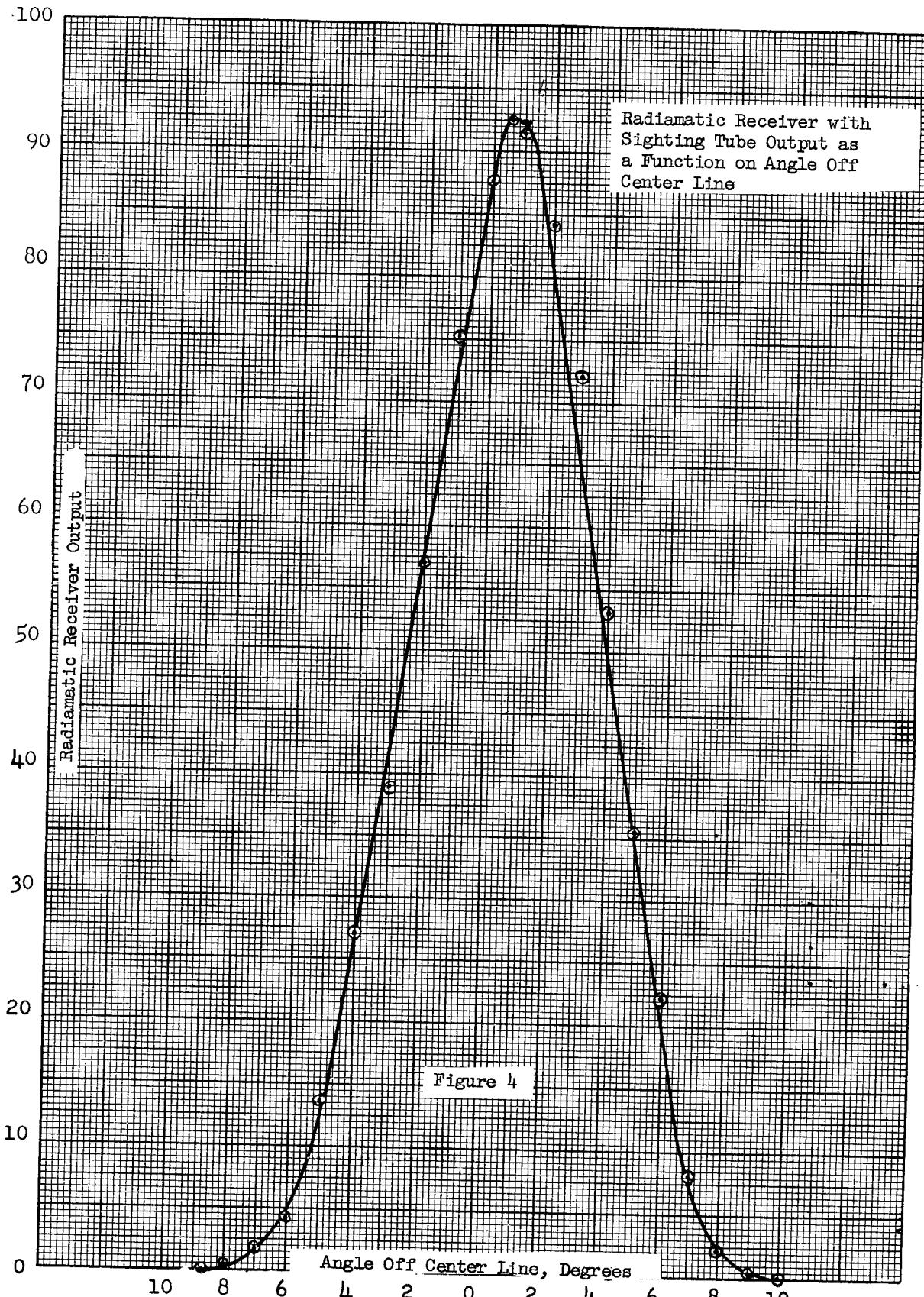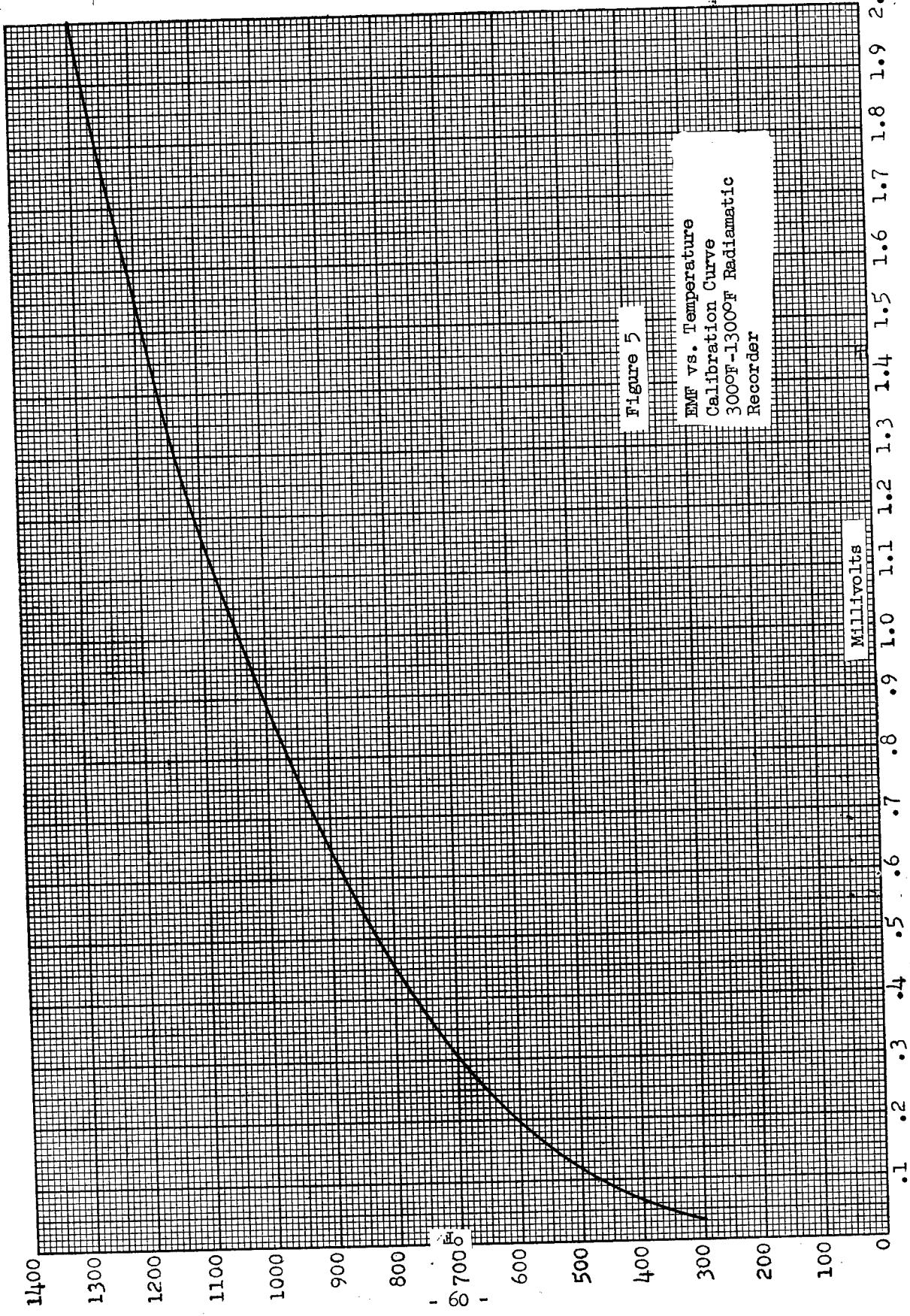
Figure 4

Figure 5

EMF vs. Temperature
Calibration Curve
300°F–1300°F Radiamatic
Recorder

Millivolts

Theoretical Curve
Experimental Points

Radiametic Receiver II-13
EMF vs. Temperature

One Run of UE-1

Figure 6

Millivolts

EMF vs. Time

Two Radiamatic Receivers
Sighting on Different Parts
of the Same Uranium Bar

Machined Surface

Oxide-Coated
Surface

Figure 7

Minutes

EMF vs. Temperature
Theoretical Curve
Experimental Points
x Machined Surface
⊙ Oxide Coated Surface

Figure 8

Millivolts

°F

- 63 -

Emittance of Clean Salt vs.
Thickness - Between 900°F
and 1100°F

Figure 9.

Thickness in Inches

Emittance

Figure 10.

Emittance of Uranium
Oxidized in Air as a
Function of Temperature

Figure 11.

°F

FIG. 12

BLACK BODY CALIBRATION FURNACE
DISASSEMBLED
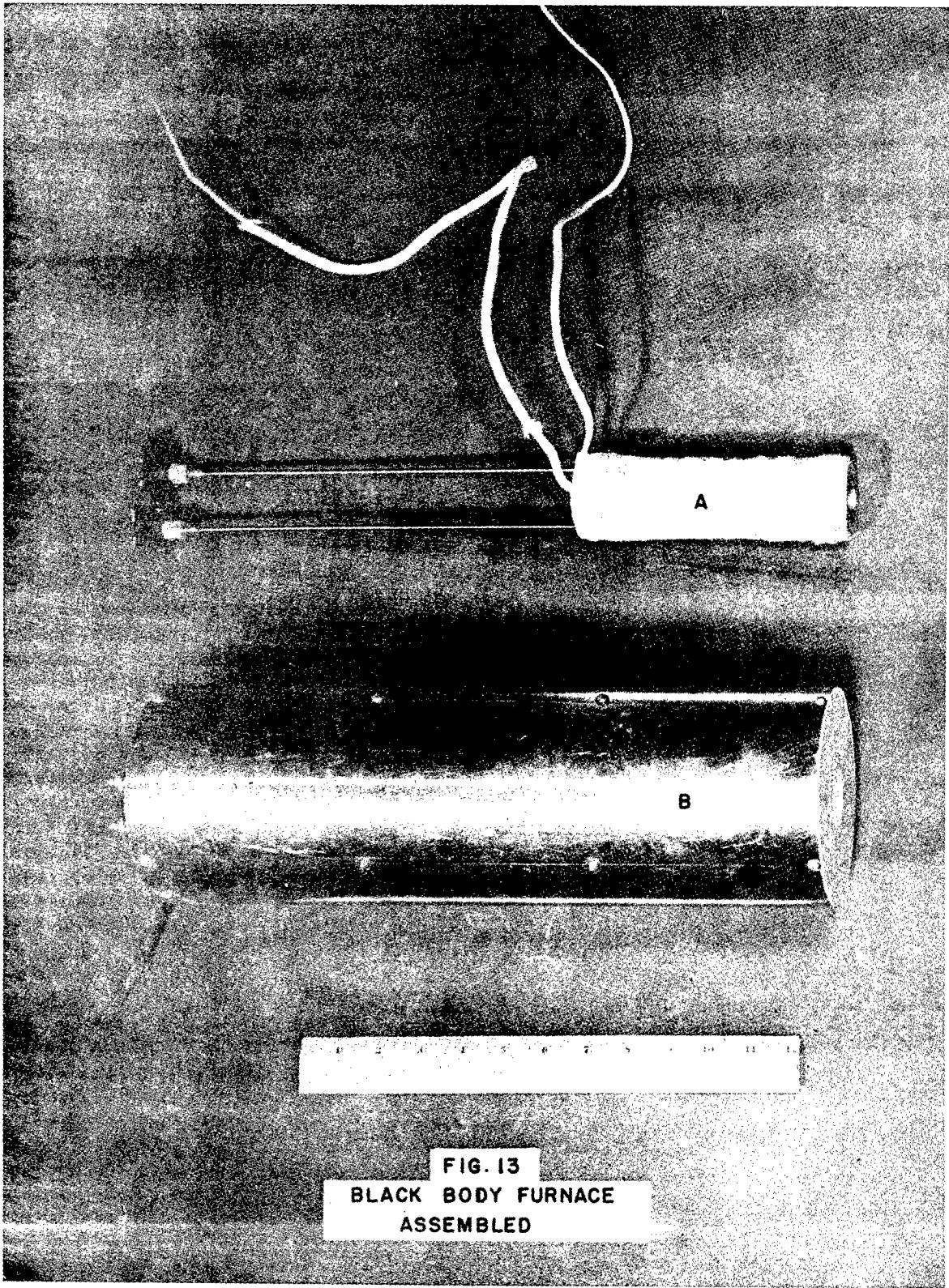
FIG. 13
BLACK BODY FURNACE
ASSEMBLED

Temperature Gradients in Blackbody Furnace

Location 1 Front End

Location 2 Back End

Figure 14.

Thermocouple Location

°F

Theoretical Curve
Experimental Points

Radiamatic Receiver Output vs. Furnace Temperature--
Check of Furnace against Theoretical Curve

Figure 15.

Millivolts

- 70 -
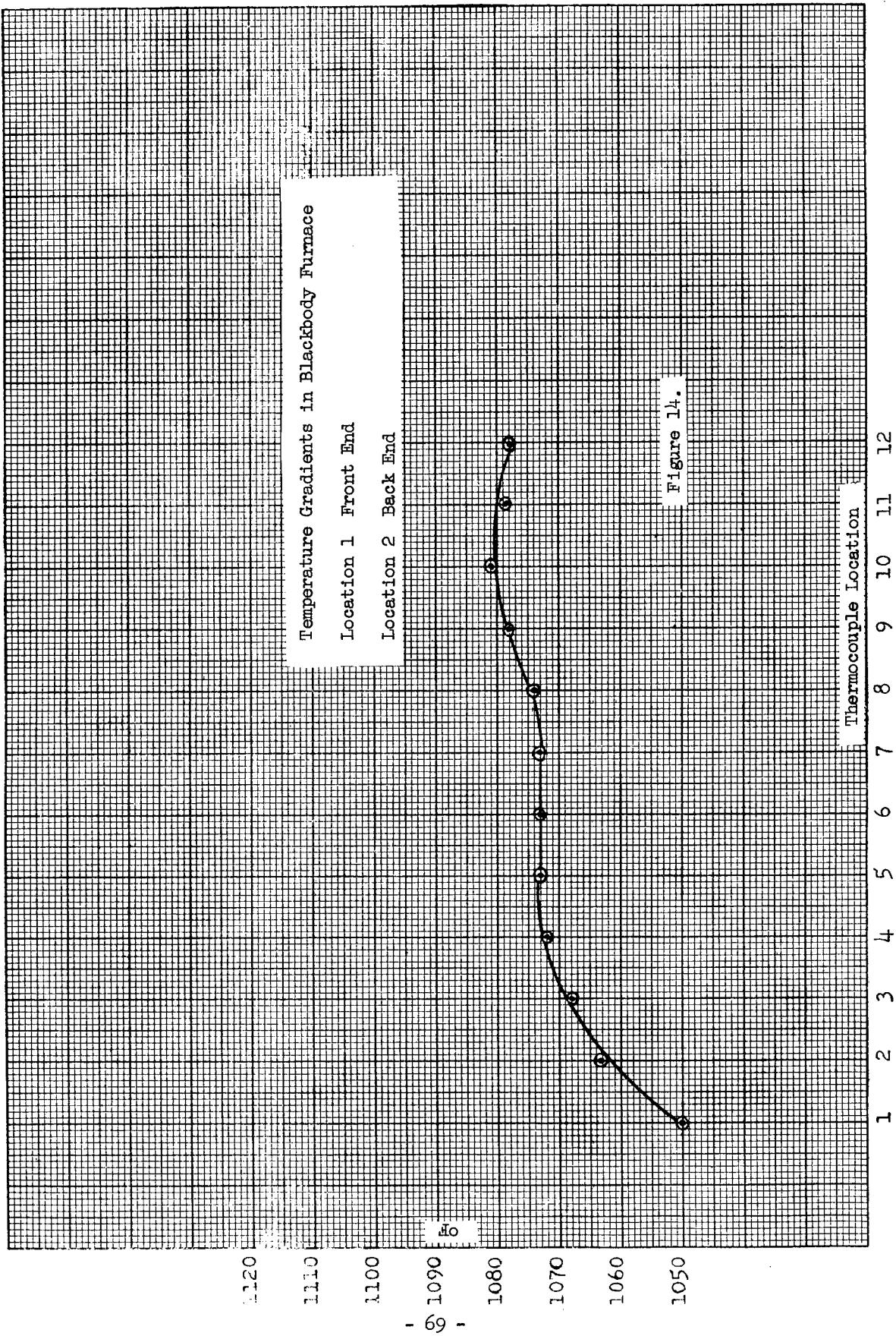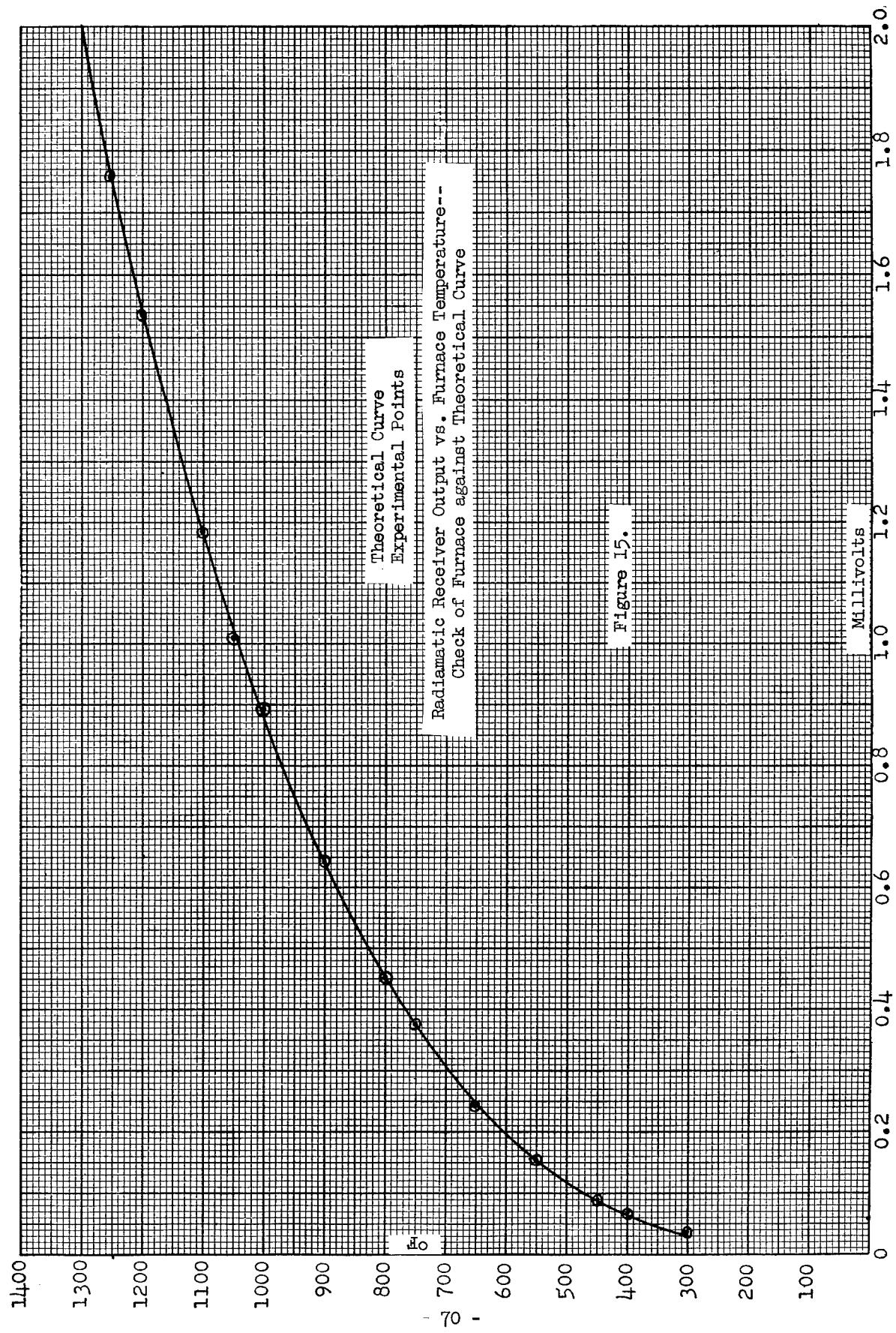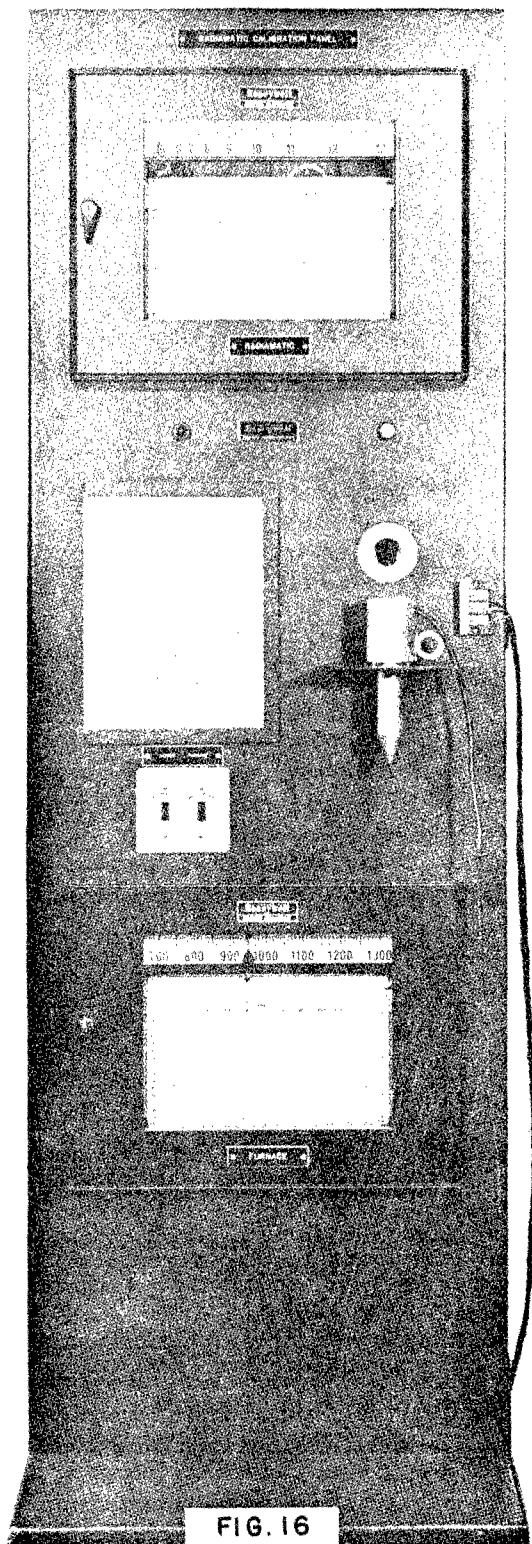
FIG. 16

RADIAMATIC CALIBRATION PANEL

FRONT VIEW
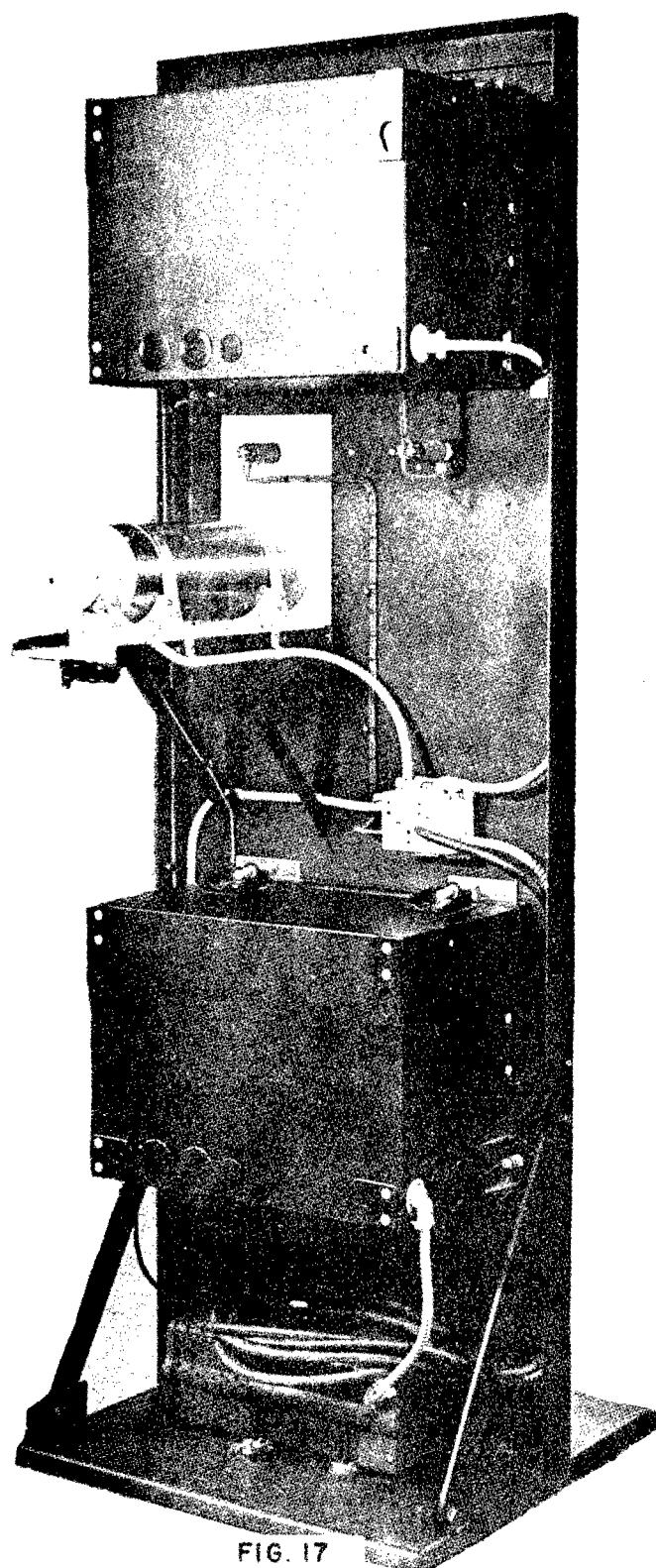
FIG. 17
RADIAMATIC CALIBRATION PANEL
BACK VIEW
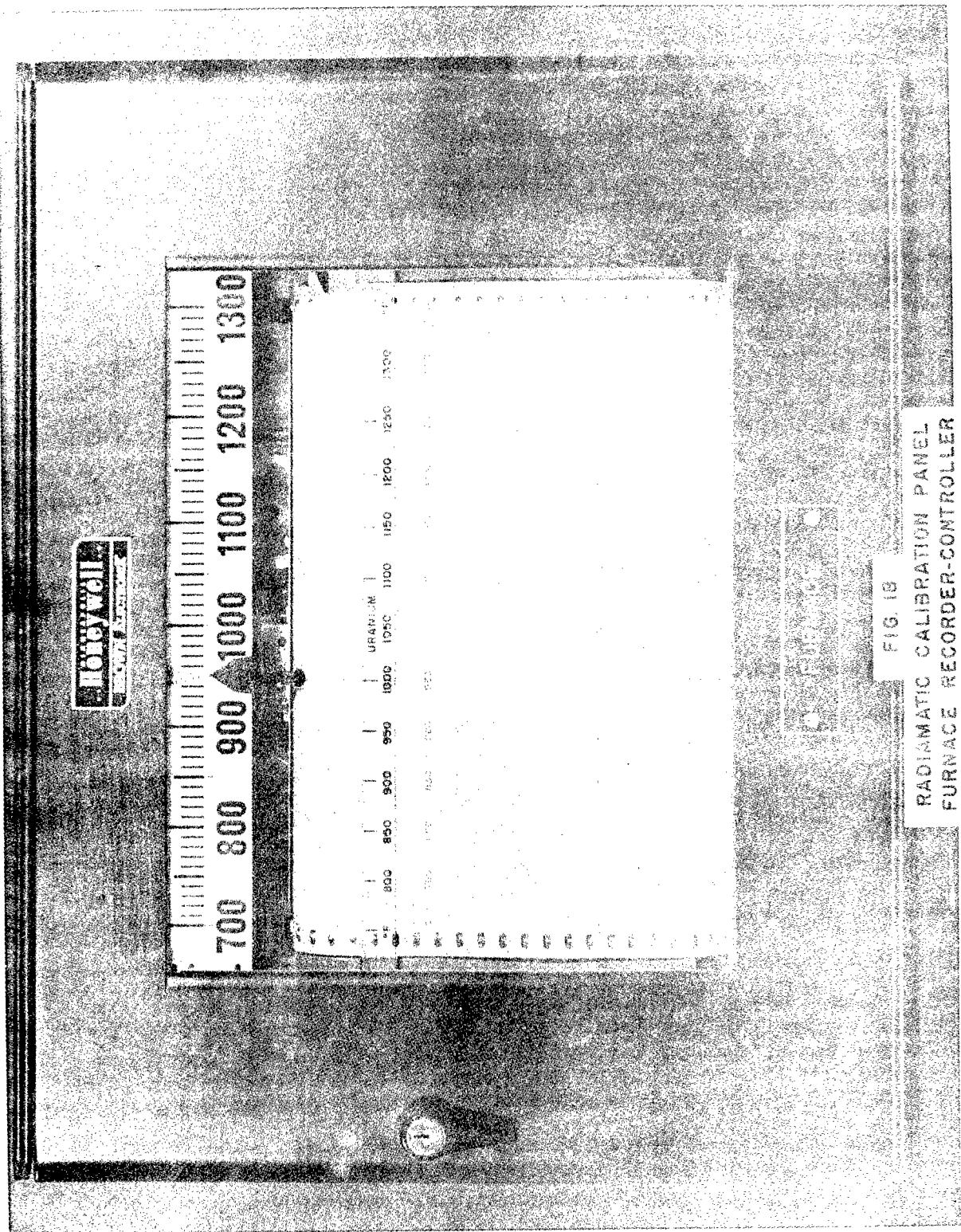
RADIOMATIC CALIBRATION PANEL
FURNACE RECORDER-CONTROLLER

FIG. 18
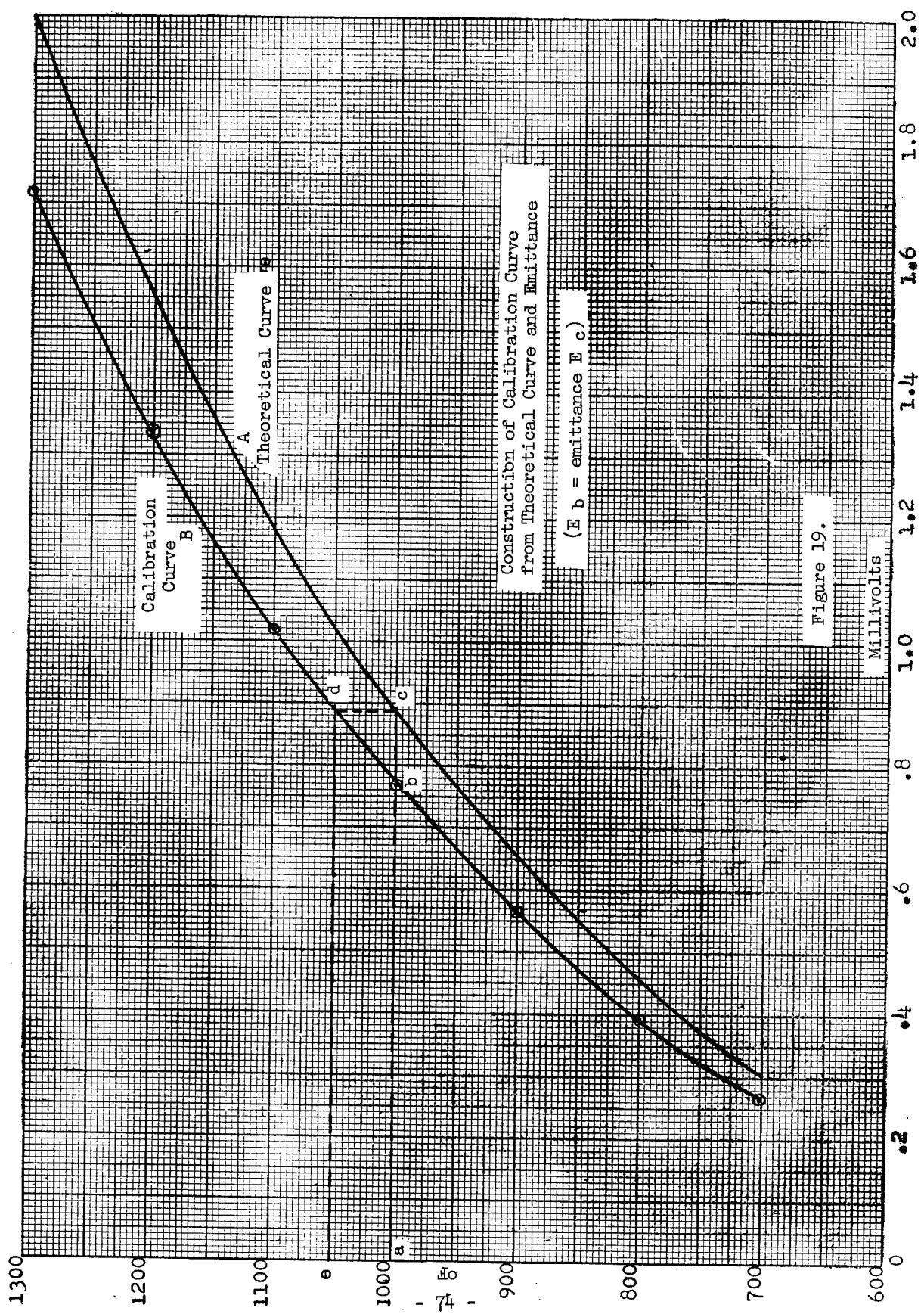
Construction of Calibration Curve
from Theoretical Curve and Emittance

(E b = emittance E c)

Figure 19.

Millivolts